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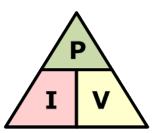
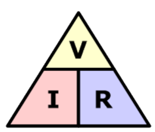
Off Grid Energy Systems Cheat Sheet

- **Force** is an influence (as a push or pull) that tends to produce a change in the speed or direction of motion of an object; force = mass x acceleration; 1 newton = 1 kg·m/s^2
- **Work** is the change in *energy* of an object due to a *force*; work = force x distance x cos ɵ; 1 joule = 1 kg·m^2/s^2 = 3600 kWh
- **Energy** is the capacity to do *work*; forms of *energy* include mechanical, electrical, chemical, magnetic, gravitational, ionization, nuclear, thermal, radiant, elastic, etc., i.e. for each kind of *force.*
- **Power** is *work* done over time (how quickly work is done).

- **Electrical force**, measured in volts (V), is the push or pull between charged particles due to electromagnetic fields (EMF). It's a vector.
- **Electrical work**, measured in kilowatt-hours (kWh), is the work done on charged particles by an electrical force. Electrical systems can do *heating work* (BTUs), *mechanical work* (HP-hours), etc., too.
- **Electrical energy**, also measured in kWh or joules (J), is the capacity to do electrical work due to potential (V) and/or current (I).
- **Electrical power**, measured in watts (W), is the rate at which electrical energy is produced or consumed; 1 W = 1 J/s = 1 Wh/h
- **Electrical current**, measured in amperes (A), is charged particles in motion due to an electrical force; 1 A = 1 coulomb/second. Electric currents produce a magnetic field perpendicular to the current flow.
- **Electrical conductors** are substances in which current can flow.
- **Electrical resistance**, measured in ohms (Ω), is a measure of the difficulty to pass a current through a conductor (similar to friction).

Watt's Law:	Power (P)	= Force (V)	x	Current (I)
	Watts	*= Volts*	*x*	*Amps*
Ohm's Law:	Force (V)	= Current (I)	x	Resistance (R)
	Volts	*= Amps*	*x*	*Ohms*





An **electrical circuit** is a path, consisting of *conductors* (wires) and/or *semiconductors* (electronics), which carry a *current* across a *voltage* gradient. Circuits may be direct current (DC) or alternating current (AC).

Voltage sources create the *voltage* – relative to **ground** – that drives the *current.* Examples of voltage sources include:

- **Batteries** – convert between chemical and electrical energy
- **Capacitors** – store electrical charge over time
- **Generators** – convert b/n mechanical and electrical energy
- **Photovoltaic cells** – convert b/n light and electrical energy
- **Thermoelectric cells** – convert b/n thermal and electrical
- **Fuel cells** – convert between chemical and electrical energy

Kirchhoff's Voltage Law: The sum of the products of the resistances of the conductors and the currents in them in a closed loop is equal to the total EMF (volts) in that loop. I.e.:

$$\boldsymbol{V}_{(source)} = \sum_{n} \boldsymbol{IR}_{n} = \boldsymbol{I}_{(circuit)} \cdot \boldsymbol{R}_{(circuit)}$$

If resistance goes to zero, current goes infinite: a **short circuit**.
And if resistance goes infinite, current goes to zero: an **open circuit**.

Kirchhoff's Current Law: the total current entering a node (a junction of two or more conductors) is exactly equal to the current leaving the node:

$$\sum_{n} I_n = 0$$

We use International System of Units **(SI) prefixes** for representing powers of numbers, such as 1000 W = 1 kW or 1/1000th V = 1 mV

Prefix	Symbol	Factor	Power
giga	G	1000000000	10^9
mega	M	1000000	10^6
kilo	k	1000	10^3
milli	m	0.001	10^{-3}
micro	µ	0.000001	10^{-6}
nano	n	0.000000001	10^{-9}

Measure	Unit	Symbol	Equivalence
Power	Watts	W	$P = V \cdot I$ or $I^2 \cdot R$ or V^2/R
Voltage	Volt	V	$V = I \cdot R$ or P/I or $\sqrt{(P \cdot R)}$
Current	Ampere	I or A	$I = V/R$ or P/V or $\sqrt{(P/R)}$
Resistance	Ohm	R or Ω	$R = V/I$ or V^2/P or P/I^2
Conductance	Siemen	G or ℧	$G = 1/R$
Capacitance	Farad	C	$C = Q/V$
Charge	Coulomb	Q	$Q = C \cdot V$
Inductance	Henry	L or H	$V_L = -L(di/dt)$
Reactance	Ohm	X	$X = \omega L - 1/(\omega C)$
Impedance	Ohm	Z or Ω	$Z^2 = R^2 + X^2$
Frequency	Hertz	Hz	$f = 1/T$

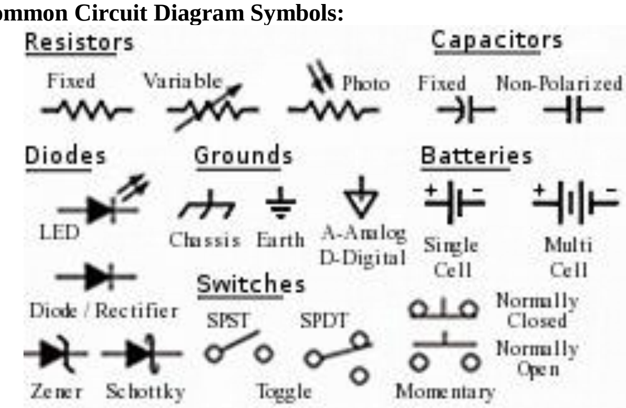
Electrical loads are circuit components or devices that consume *energy* to do *work*. Loads are a type of *resistance* and cause a *voltage drop* and/or *current drop* across them. Types of loads include:

- **Resistance Heating** (1,000 to >20,000 W) - range, toaster, dryer, water heater, baseboards
- **Compressors** (500 to 6,000 W) - refrigerators, air conditioners, dehumidifiers, heat pumps
- **Pumping** (20 to 5,000 W) - well water, septic, heating circulator pumps, sump pumps
- **Motors** (1 to 500 W) - fans, power tools, washer
- **Lighting** (1 to 100 W) - incandescent, CFL, LED
- **Electronics** (<1 to 300 W) - computers, TVs, DVRs, clocks, thermostats, security system
- **Phantom** (<1 to 15 W) - small persistent loads such as power indictor lights; remote standby power; etc.

The voltage sources and loads may be either in **series** (positive leg from one goes to negative of the next, i.e. *daisy chained*) or **parallel** (all positives are on one side, all negatives on the other).

- For series components, voltages are summed, resistances are summed, and *current is constant*.
- For parallel components, *voltage is constant*, currents are summed, and the total resistance is the inverse of the sum of the inverses of the resistances.

Common Circuit Diagram Symbols:



Being “**off-grid**” means providing for substantially all of your own needs, including *electricity*, *heat*, *water*, *sanitation*, and *food*. Electricity is often instrumental to providing most of these other needs, e.g., pumping water, circulating heat, and refrigerating food. Excess production is stored on-site in batteries for times of deficit. To convert an existing building to off-grid or to build a new off-grid home, it will take some assessment and planning.

<u>Energy Usage Estimation & Optimization:</u>

- In a spreadsheet, record all of your electrical devices.
- Look up wattages in product manuals, online databases, the info plate/sticker on the device, or record the output of a watt meter on each device.
- Multiply device wattages by a conservative estimation of how long they will be on each day to get kWh/day for each device.
- Target the largest users of energy for upgrade or replacement, including using a different fuel source for heating loads; target the low hanging fruit next (e.g. lightbulbs); then upgrade older devices that come with additional benefits from upgrading.
- Alternatives to electric resistance heating include:
    - *Propane* (or *natural gas*) is an easy replacement for ranges, ovens, dryers, hot water, and space heaters.
    - *Passive solar* is the most efficient off-grid energy technology. It can provide significant space heating.
    - *Solar thermal* is the next most efficient. It can take over virtually all space and water heating.
    - *A wood stove* will provide plenty of space heating and also can do cooking and even water heating.
    - *Solar ovens* and *dehydrators* can do some food prep.
    - *Clotheslines* are effective at drying clothes.
- Consider behavioral / lifestyle changes that will save energy.
- Install motion sensors, timers, insulation, & thermal mass.
- Consider targeting a lower peak threshold before you’ll resort to running an on-demand generator.
- Your final optimized daily energy requirement in kWh, which is the sum of individual device kWh, will be the basis of designing your off-grid system.

<u>Sizing your Batteries:</u>

1. Determine how long you want to run your off-grid energy system on batteries without any inputs. 20 hours should be the minimum to reach rated battery output and lifespan. More than 2 days will probably be cost prohibitive. Somewhere between 24 and 36 hours is the sweet spot.
2. Multiply your estimated usage by the time you decide, e.g.:
   10 kWh/day x 30 hours x 1 day/24 hours = 12.5 kWh
3. Since you don’t want to go below 80% depth of discharge (DoD), divide by 80%. E.g. 12.5 / 0.80 = 15.63 kWh
4. Factor in 15% system losses, e.g. 15.63 x 1.15 = 17.98 kWh
5. Convert to amp-hours (Ah), since that’s how batteries are sized. To do so, divide the watt-hours by the voltage of your system (Watt’s Law), e.g.: 17980 Wh / 24 V =~ 750 Ah, or for a 12 V system, 17980 Wh / 12 V =~ 1500 Ah.
6. Find a combination of quality deep-cycle batteries that in series and/or parallel strings adds up to your system voltage and desired amp-hours. E.g. if you use Rolls-Surrette 4CS17P batteries, which are 546 Ah @ 4V (20 hour rate), then three in a series string gives you 546 Ah @ 12 V, and three such strings in parallel gives you 1638 Ah @ 12 V. And if you go by the 30 hour rate, it’s more like 1800 Ah @ 12 V, which exceeds your minimum requirements by a decent margin, which means you can either go longer or a shallower DoD, which is good.

<u>Balance of System:</u>

1. As a general rule of thumb, you should select a solar PV array of sufficient wattage to charge your batteries in 8 hours. So if you have 1800 Ah @ 12 V, or 21.6 kWh, then you need an array of 21.6 / 8 = 2.7 kW, which would be 14 x 200 W panels or 10 x 270 W panels. If you are using a hybrid system that includes wind or micro-hydro, etc., then you can divide that 2.7 kW between the different sources, e.g. 1 kW wind turbine + 9 200 W solar panels, though this will depend on your available wind resource as well.
2. Choose a solar charge controller big enough to handle your PV array. Controllers are measured in amps, so divide your PV array’s wattage by the nominal battery voltage. E.g.: 2700 W / 12 V = 225 A. Most charge controllers are multiples of 20 A, so you might choose 3 x 80 A charge controllers or 4 x 60 A charge controllers for a 225 A array and split the panels between the controllers. If using PWM controllers, the PV panels and controllers must be the same nominal voltage as the batteries (and panels wired in parallel). If using MPPT controllers, the panels can be wired in series to be much higher than the nominal battery voltage. Likewise with sizing wind, hydro, etc., controllers, which might need to be rated for that particular source.
3. Add an on-demand power source, such as a propane generator, for backup during long periods of overcast days or high-demand times. The generator only needs to be about the same size, in watts, as the PV array, which will be among the smallest gen sets as you can find. Use an adequately sized AC battery charger with the generator.
4. Add inverters, DC-DC converters, and other loads to the batteries depending on your needs.
5. Use adequate wire gauges for the ampacity and voltage drop of each circuit. National Electric Code prescribes minimums:

Table 310.15(B)(17)
Allowable Ampacities of Single Insulated Conductors
Rated 0 - 2000 Volts, In Free Air,
Based on Ambient Air Temperature of 30°C (86°F)

Size	Temperature Rating: 60°C (140°F) Types TW*, UF*	75°C (167°F) Types FEPW*, RHW*, THW*, XHHW*, RH*, THHW*, THWN*, ZW*	90°C (194°F) Types TA, SIS, MI, THHN*, THWN-2, XHHWT, TBS, FEP*, RHH*, THHW*, USE-2, XHHW-2, SA, FEPB*, RHW-2, THW-2, XHH, ZW-2
18 AWG	–	–	18
16 AWG	–	–	24
14 AWG	25*	30*	35*
12 AWG	30*	35*	40*
10 AWG	40*	50*	55*
8 AWG	60	70	80
6 AWG	80	95	105
4 AWG	105	125	140
3 AWG	120	145	165
2 AWG	140	170	190
1 AWG	165	195	220
1/0 AWG	195	230	260
2/0 AWG	225	265	300
3/0 AWG	260	310	350
4/0 AWG	300	360	405

Conductor Size for 3% Drop in Voltage

Current (Amps)	Round-Trip Length of Conductor (Feet): 10	20	30	40	60	80	100	120	140
	Minimum Wire Size (AWG)								
1	16	16	16	16	16	14	14	14	12
2	16	16	16	14	14	12	10	10	8
5	16	14	12	10	10	8	6	6	6
10	14	10	10	8	6	6	4	4	2
15	12	10	8	6	6	4	2	2	1
20	10	8	6	6	4	2	2	1	0
25	10	6	6	4	2	2	1	0	2/0
30	10	6	4	4	2	1	0	2/0	3/0
40	8	6	4	2	1	0	2/0	3/0	4/0
50	6	4	2	2	0	2/0	3/0	4/0	
60	6	4	2	1	2/0	3/0	4/0		
70	6	2	1	0	3/0	4/0			
80	6	2	1	0	3/0	4/0			
90	4	2	0	2/0	4/0				
100	4	2	0	2/0	4/0				

6. Ensure adequate fusing and breakers to protect the weakest components in the system.
7. Ground the system at just one location near the battery bank on the negative side. Do not use more than one earth ground.